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An Analytical Model for Calculation of the Steel Hardness after Continuous Cooling

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Abstract. A number of modern engineering steel grades were analyzed using the CCT diagrams plotted by means of the dilatometer. The statistical analysis of the experimental data allowed for the determination of the equations connecting the critical cooling rate to achieve fully martensitic microstructure and the martensite hardness with the chemical composition of the steel. The dependence of the steel hardness on the cooling rate in the range of 0.1...30 °C/s was determined. It was shown that this dependence had the logarithmic character for every studied steel grade. The equations connecting the coefficients of the logarithmic function with the chemical composition of steel were obtained.

1. Introduction

Steel is the most widely used material in the industry. By varying the chemical composition of steel and the technological parameters of its heat treatment (heating temperature, cooling rate, etc.), microstructure constituents with different morphology and properties can be obtained: ferrite, pearlite, upper and lower bainite, martensite, residual austenite [1–3]. There are a lot of calculation methods that allow predicting the microstructure and mechanical properties of steel after the implementation of various heat treatment processes with different accuracy [4–8]. In this paper, we analyze the results of dilatometric studies of modern engineering steels [9–14] in order to identify the relations in the microstructure and hardness formation during the continuous cooling.

2. Experimental

The commercial and experimental engineering steels of various alloying systems were studied: Cr-Ni-Mo, Cr-Mn-Mo, Cr-Mn-Si-Ni-Mo, Cr-Mo-V (Table 1).

The transformations of the austenite under continuous cooling conditions were studied by means of Linseis L78 R.I.T.A. dilatometer using cylindrical specimens (diameter 3...6 mm, length 10 mm). The austenitization parameters were $A_{c3} + 30...50$ °C, 15 minutes. Continuous cooling was carried out at constant cooling rates 0.1...30 °C/s. Analysis of dilatometric data was carried out according to the method described in [15, 16]. The microstructure was studied using MEIJI IM7200 optical microscope. The steel hardness was determined using the Rockwell hardness tester (scale C). At least three hardness measurements were performed on each dilatometric specimen.



Table 1. Chemical composition of the studied steels, wt. %.

Steel	C	Cr	Mn	Si	Ni	Mo	V	W	S	P
20Cr2Ni2Mo	0.18	2.13	0.35	0.07	2.17	0.40	0.010	-	0.024	0.025
20Cr2Ni4	0.17	1.31	0.42	0.23	3.33	0.02	0.007	-	0.011	0.014
25Cr2Ni4Mo	0.24	1.43	0.34	0.28	4.06	0.32	0.000	0.07	0.005	0.005
38CrNi3Mo	0.36	0.87	0.37	0.26	2.80	0.21	0.003	0.02	0.009	0.005
38CrNi3MoV	0.32	1.26	0.33	0.27	3.02	0.34	0.125	0.02	0.001	0.006
31NiCrMo13-4	0.31	1.08	0.53	0.23	3.10	0.23	-	-	0.018	0.009
HY-TUF	0.24	0.34	1.38	1.55	1.69	0.40	0.010	-	0.023	0.019
20Cr2Mn2SiNiMo	0.18	2.35	1.99	1.03	1.17	0.34	0.007	-	0.018	0.013
20Cr2MnSiNi2Mo	0.15	2.55	0.67	0.76	2.31	0.77	-	0,02	0.014	0.013
30Cr2MnSiNi2WMo	0.26	1.76	1.14	0.94	2.15	0.37	0.008	1,11	0.001	0.007
30CrMnSiNi2	0.29	1.08	1.13	0.98	1.51	0.04	0.005	-	0.001	0.005
20CrMn2NiMo	0.21	1.04	1.70	0.01	1.18	0.31	0.005	-	0.019	0.025
25CrMnMo	0.26	0.68	0.87	0.24	0.01	0.21	-	-	0.009	0.009
38CrMnMo	0.37	0.81	0.64	0.24	0.09	0.15	-	-	0.004	0,011
42CrMo4-mod1	0.43	0.97	0.91	0.24	0.13	0.16	0.003	-	0.008	0.007
42CrMo4-mod2	0.42	1.10	1.05	0.24	0.31	0.55	0.001	-	0.007	0.007

3. Results and discussion

The values of the critical cooling rate, v_M , corresponding to the minimum cooling rate at which a completely martensitic microstructure is formed, were determined from the CCT-diagrams of the studied steels. An equation relating the critical cooling rate, v_M , with the chemical composition of steel, wt. %, was obtained using the regression analysis of the experimental data.

$$v_M = 62,5 - 89,7C - 7,3Cr - 5,7Mn - 9,1Si - 6,7Ni - 1,0Mo + 16,9V + 7,2W. \quad (1)$$

A verification of the equation (1) by means of the Fisher criterion showed that the obtained model had a satisfactory adequacy: the ratio of the theoretical value of the Fisher criterion to the calculated one was more than 40. It should be noted that the majority of the alloying elements taken into account in equation (1) reduce the value of the critical cooling rate, i.e., increase the hardenability of steel. The only exceptions are the strong carbide-forming elements – vanadium and tungsten. Their presence in the steel composition, even as the impurities, increases the critical cooling rate. This is explained by the formation of the dispersed and hardly soluble carbide particles in steels alloyed with vanadium and tungsten. These particles serve as substrates for the formation of a new phase during the austenite transformation below A_{r3} .

The dependence of the hardness on the cooling rate was determined for each studied steel grade. It was found that for all the steels under consideration the hardness values were in a logarithmic dependence on the cooling rate (until a completely martensitic microstructure was obtained). Figure 1 plots the typical examples of the hardness dependence on the cooling rate for the steels of various alloying systems. The experimental data were satisfactorily described by a logarithmic function.

$$HRC = k \cdot \ln(v_{cool}) + h_1, \quad (2)$$

where HRC – the hardness of steel; v_{cool} – cooling rate, °C/s; k , h_1 – the constant parameters. The parameter k corresponds to the slope of the dependence of hardness on the cooling rate in logarithmic scale. The parameter h_1 corresponds to the hardness of steel at a cooling rate 1 °C/s.

The values of the parameters k and h_1 depend on the chemical composition of the steel. The following equations were obtained using the regression analysis of the experimental data (the content of alloying elements in wt.%):

$$k = 6,01 + 13,83C - 0,74Cr - 2,74Mn + 1,33Si - 1,13Ni - 2,78Mo - 1,57W, \quad (3)$$

$$h_1 = -12,69 + 89,71C + 2,62Cr + 8,34Mn + 4,61Si + 6,73Ni + 17,45Mo. \quad (4)$$

Note that the carbon content had the highest effect on the values of the parameters k and h_1 , and the chromium content had the least effect. An increase of any alloying element content led to an increase in the parameter h_1 value. This is due to the fact that all the alloying elements taken into account increase the hardenability of steel and, consequently, the amount of martensite in the microstructure at a certain cooling rate (particularly at 1 °C/s).

An increase in the content of Cr, Mn, Ni, Mo, W in steel led to a decrease in the parameter k value, which characterized the slope of the dependence of the hardness on the cooling rate in a logarithmic scale. This fact is explained by the effect of the alloying on the increase of the range of the cooling rates at which martensite is formed. As a result, the hardness values are less dependent on the cooling rate. Si and C, on the contrary, increased the value of the parameter k , and, accordingly, the slope of the dependence of hardness on the cooling rate, which is probably due to the influence of these elements on the hardness of the α phase (martensite and bainite).

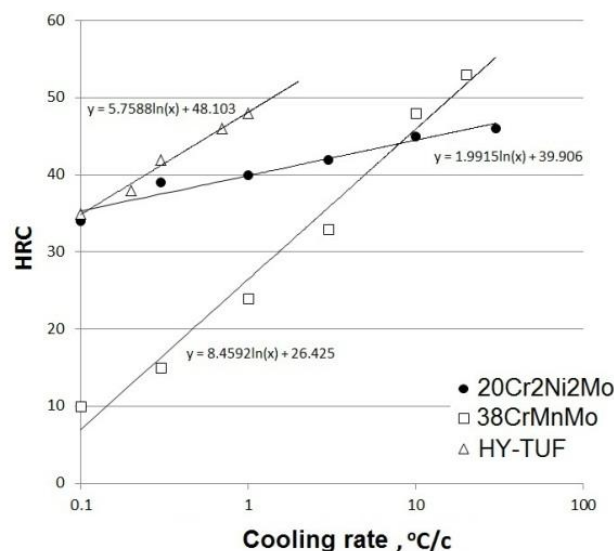


Figure 1. The dependence of hardness on the cooling rate for different steels grades.

The dependence of the hardness of martensite on the content of alloying elements was determined by means of the regression analysis of experimental data:

$$HRC_M = 33,40 + 55,49C + 2,04Si, \quad (5)$$

where HRC_M – the hardness of martensite; C, Si – the carbon and silicon content, wt. %.

Thus, knowing the chemical composition of the steel and using equations (1–5), it is possible to determine the hardness of the steel after cooling at any cooling rate in the range of 0.1...30 °C/s with the acceptable accuracy. This, in turn, will make it possible to evaluate the strength characteristics of steel (yield strength and tensile strength) according to the known dependences [17–19].

The following algorithm was proposed for calculating of the hardness of steel obtained after the continuous cooling at different rates:

- the critical cooling rate, v_M , is determined by equation (1);

- the parameters of the logarithmic equation (2), k and h_1 , are determined by equations (3) and (4), respectively;
- the hardness of steel is determined according to equation (2) in the range of cooling rates from $0.1\text{ }^{\circ}\text{C/s}$ to v_M ;
- the hardness of martensite is determined by equation (5).

Figure 2 shows the examples of the comparison between the experimental dependences of hardness on the cooling rate (both for the steels studied in this work and for the steel from the reference [20]) with the results of calculations by the proposed model. As can be seen, the analytical equations give an adequate prediction of the hardness values.

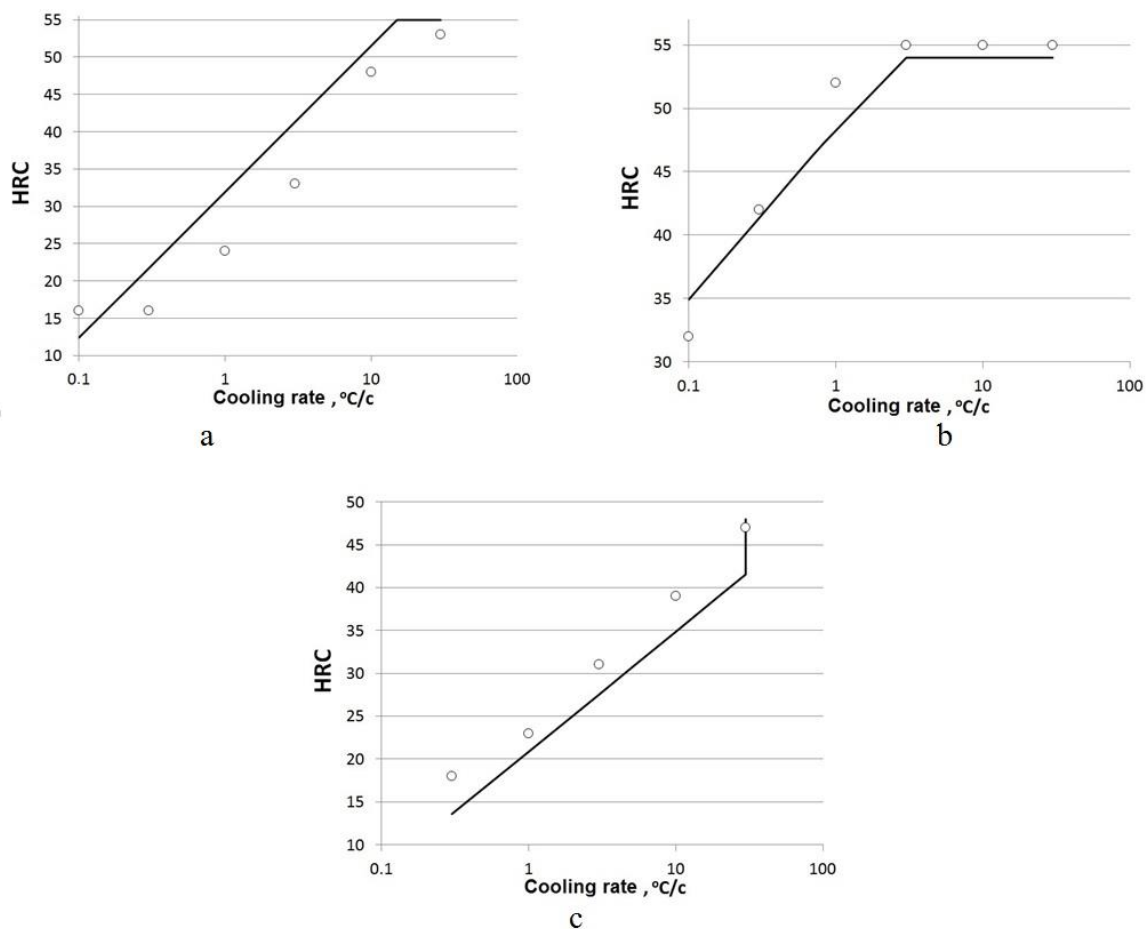


Figure 2. Experimental and calculated dependences of the hardness of steel on the cooling rate: a) 38CrMnMo; b) 38CrNi3Mo; c) 25CrMnV [20].

4. Conclusions

The dependence of the critical cooling rate on the chemical composition of steel was determined. The strong carbide-forming elements (V, W) increased the critical cooling rate, i.e., reduced the hardenability of steel, since these elements formed hardly soluble dispersed carbide particles acting as the substrates for the formation of a new phase.

The logarithmic dependence of the steel hardness on the cooling rate was obtained. The parameter k of the logarithmic equation corresponds to the slope of the dependence of hardness on the cooling rate in logarithmic scale, and the parameter h_1 corresponds to the hardness of steel at a cooling rate $1\text{ }^{\circ}\text{C/s}$. Equations relating the parameters of the logarithmic equation, k and h_1 , with the chemical composition of steel were determined.

An algorithm has been developed that allows to determine the steel hardness obtained after the continuous cooling at constant rates 0.1...30 °C/s using the chemical composition of steel.

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